BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B70 06019

SUBJECT: Launch Site Recovery of Ballistic Boosters
Case 105-4

DATE: June 9, 1970

FROM: E. D. Marion

ABSTRACT

Two-stage ballistic booster systems were analyzed to evaluate the feasibility of returning the first stage to the launch site with a post-separation impulsive maneuver. The analysis considered effects of trajectory conditions at the time of staging and the effects of the recovery maneuver on vehicle sizing. The results indicated that the maneuver has some attractive features from the standpoint of recovery operations and vehicle sizing and is feasible from the standpoint of flight mechanics. Some operational problems may exist because of a requirement for a) rapid engine restart, b) vehicle flight at high angle of attack, and c) rapid vehicle reorientation.

Although these problems warrant further evaluation, on the basis of this preliminary assessment the maneuver appears to be both feasible and useful.

(NASA-CR-110638) LAUNCH SITE RECOVERY OF BALLISTIC BOOSTERS (Bellcomm, Inc.) 13 p

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FF No. [redacted] (CODE)
(NASA CR OR TMX OR AD NUMBER) // (CATEGORY)
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MEMORANDUM FOR FILE

1.0 Introduction

Attention has recently been focused on shuttle concepts based on recoverable booster systems that are configured as ballistic entry vehicles. These ballistic boosters are usually conceived as single stage to orbit systems. Although this is possible because of the relatively high mass fractions attainable with this design concept, the resulting vehicles are extremely sensitive to inert weight growth. This leads more or less directly to the idea of tandem staging of ballistic boosters. Ostensibly, this could avoid the high sensitivities of single stage systems and keep the structural efficiencies of ballistic systems. But as usual, it isn't that simple, and the principal problem now becomes one of getting that first stage back to the launch site.

2.0 Mission Profiles

Several ways of returning the ballistic booster to the launch site are possible; they are shown on Figure 1.

The first possibility is to execute an impulsive maneuver immediately after staging, that would put the booster on a high lofted trajectory ending back at the launch site. This is called impulsive return to the launch site, or less elegantly, lob-retro.

A second possibility would be to fly the unloaded booster on to orbit, where it could wait for the right opportunity to re-enter and land at the launch site. The choice between these two is dependent primarily on where staging occurs. If it is closer, energetically speaking, to the launch site than it is to orbit, then the lob-retro maneuver would offer a significant advantage.

A third set of possibilities involves landing the booster down range. From there it could; 1) be refueled and flown ballistically back to the launch site on the main propulsion engines, 2) use lift fan-jet engines to fly back to the launch site, or 3) be carried back to the launch site via surface transportation.

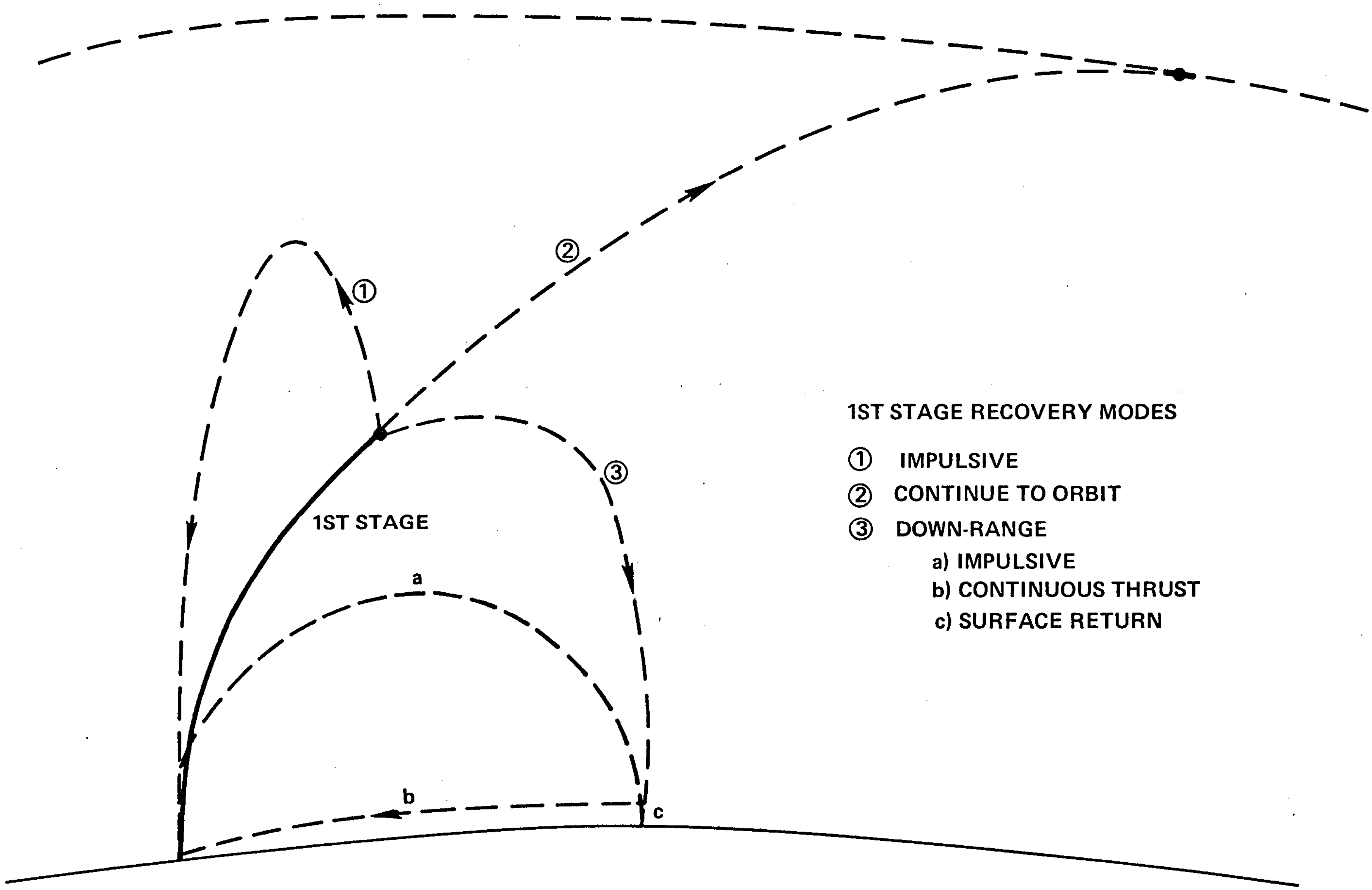

FIGURE 1. BALLISTIC BOOSTER
MISSION PROFILES

Of all these possibilities, the most novel is the lob-retro maneuver. It represents the largest deviation from the current way of doing business, and is the least studied and understood. The purpose of this memorandum is to present some preliminary considerations about this unusual maneuver and its effect on vehicle size selection.

3.0 Impulsive Requirements

A vector diagram of the lob-retro maneuver is shown in Figure 2. The flight velocity, u, and the flight path angle, γ, define the initial conditions for the maneuver. Given the range and altitude at staging, the family of required return velocity vectors can be defined in terms of the needed return velocity, V, and return flight path angle, α. The initial conditions shown are from a typical launch trajectory, although the lob-retro calculations assumed a flat, static and airless earth.

From any point along the flight path, a number of return trajectories are possible, however, two cases will be of interest. One case is when the difference between the flight vector and the return vector is the smallest. This case defines the minimum impulsive ΔV needed to execute a lob-retro maneuver and is shown in Figure 2 as $\overline{\Delta V}_{min}$. Since the landing ΔV is independent of the return trajectory, $\overline{\Delta V}_{min}$ produces the minimum total recovery ΔV.

This maneuver would require that the vehicle thrust approximately along the line of $\overline{\Delta V}_{min}$. The vehicle would have to be oriented base forward, and maintained at some angle of attack during the burn. The angle between $\overline{\Delta V}_{min}$ and the flight velocity vector $\bar{u}$ is essentially the required angle of attack. As the maneuver progresses, the flight velocity vector will rotate from $\bar{u}$ to $\bar{V}$, with the point of the vector tracing the path along the $\overline{\Delta V}_{min}$ vector. At one point during this maneuver the vehicle must fly at 90° angle of attack.

If these high angles of attack are unacceptable, the maneuver can be flown a different way; the vehicle can first be oriented base forward at zero angle of attack and burned to reduce $\bar{u}$ to zero. It then must be oriented to the proper return flight path angle, α, and burned a second time to produce the right $\bar{V}$. The total ΔV in this case is the scalar sum of $\bar{V}$ and $\bar{u}$. And since $\bar{u}$ is fixed, the maneuver ΔV can be minimized by minimizing $\bar{V}$. This is the second case shown on Figure 2 as $\bar{V}_{min}$.

The lob-retro ΔV is influenced by the flight velocity, the range, altitude, and flight path angle. The sensitivity of the lob-retro ΔV's to these variables is shown in Figure 3. The most important variables are clearly range and flight velocity, both of which tend to favor an early staging. The

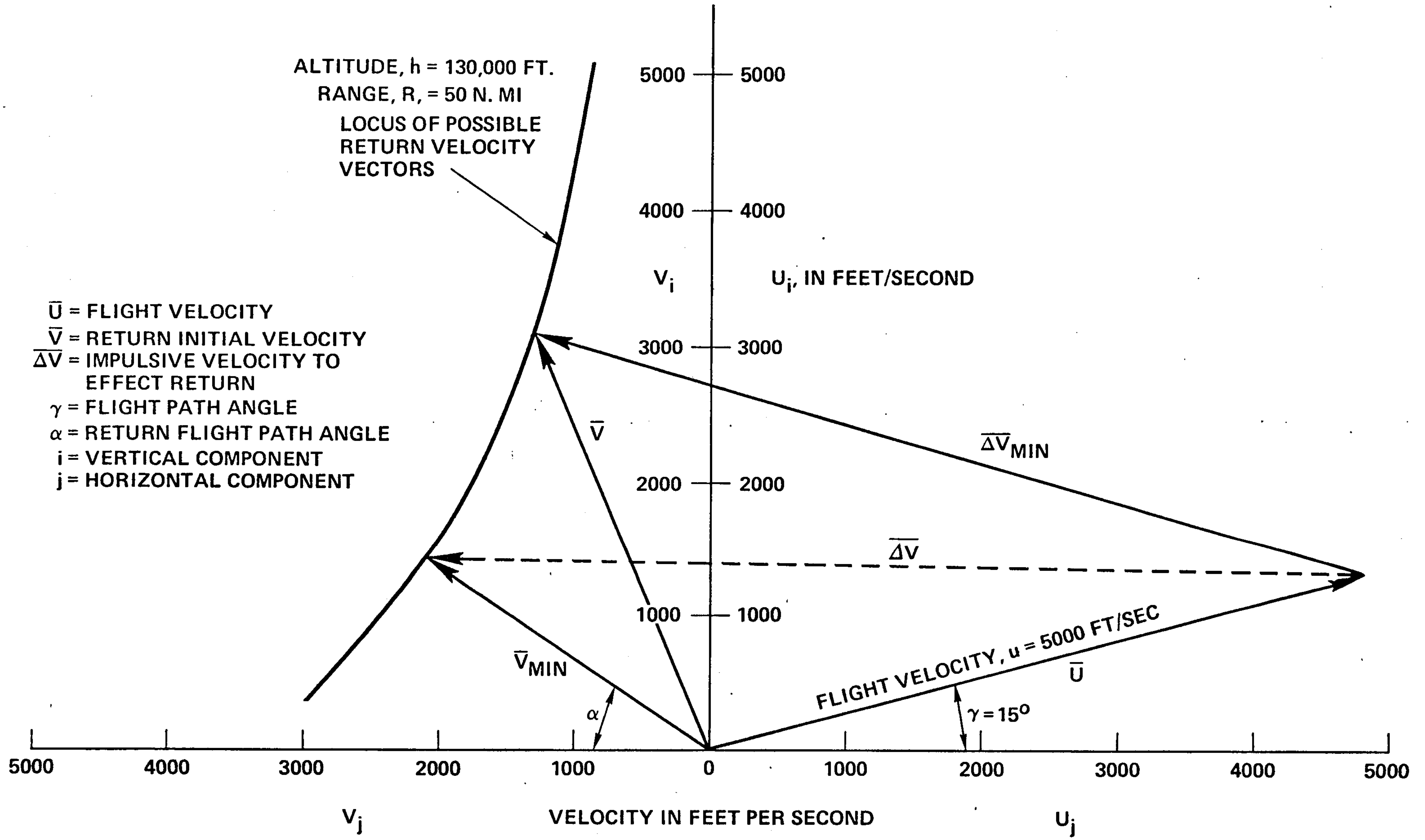

FIGURE 2. IMPULSIVE RETURN TO LAUNCH SITE VECTOR ANALYSIS

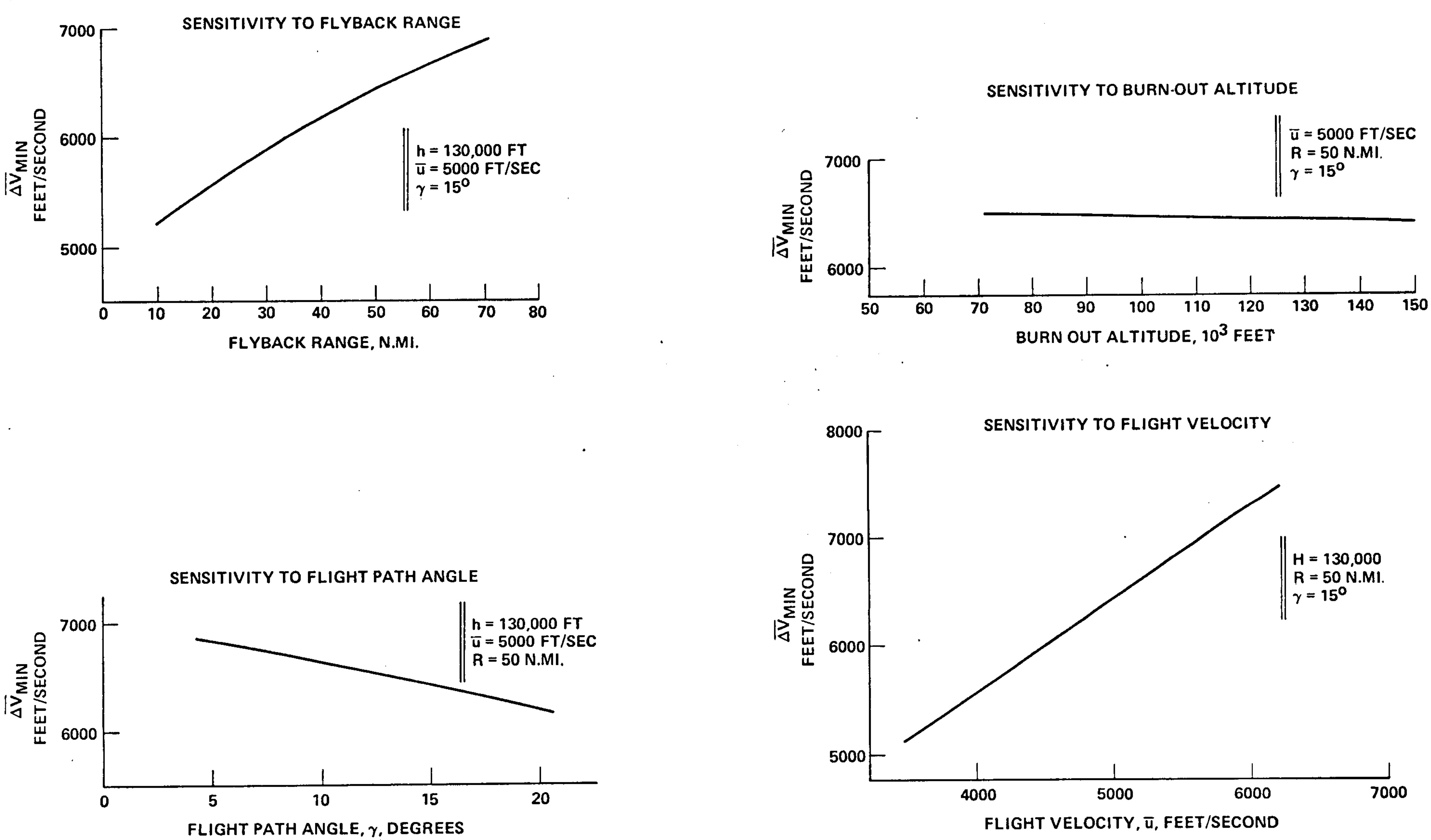

FIGURE 3. IMPULSIVE RETURN TO LAUNCH SITE SENSITIVITY ANALYSIS

general characteristics of the maneuver also tend to favor a more lofted trajectory than normal.

For a given trajectory the lob-retro ΔV's are a strong function of the staging time. This is shown in Figure 4 where both flight velocity and lob-retro ΔV's are plotted against impulsive velocity delivered by the booster. The upper bound on the ΔV band corresponds to V_{min} and the lower bound corresponds to ΔV_{min}.

The ΔV's in most cases are similar to or larger than the actual flight velocity, but smaller than the total impulsive velocity delivered to that point. To verify the vector analysis a trajectory simulation was made for a single point along the launch trajectory. The point chosen was a flight velocity of 5,000 fps at a range of about 33 miles. The resulting lob-retro trajectory is shown in Figure 5 with histories for the various trajectory parameters given in Figure 6. The trajectory corresponds to a minimum ΔV maneuver.

The vector analysis treats the lob-retro maneuver as a point impulse, while Figures 5 and 6 indicate that conditions change significantly between the beginning and the end of the lob-retro burn. In spite of this, the trajectory analysis shows good agreement with the vector analysis. A quick evaluation of the trajectory data indicated that the finite impulse introduces finite but small differences. Consequently the vector analysis should be adequate for preliminary sizing analyses.

The effects of a delay in the lob-retro burn until some time after apogee were briefly examined. In general, the lob-retro maneuver should be initiated some time between staging and apogee. For further delays, the increasing range and decreasing altitude more than offset the decreasing flight velocity. In fact, the analysis suggests that lob-retro should be initiated as soon as possible after staging, therefore, further study is needed before definitive statements can be made.

4.0 Vehicle Sizing

The effects of the lob-retro maneuver on vehicle sizing are startling. In a two stage system, the ΔV split is usually selected to give the minimum gross weight on the pad. The result of a typical parametric study involving a ballistic booster is shown in Figure 7. The weight of each stage, and the total on-pad weight for the system is plotted as a function of the ΔV split between the booster and the orbiter. For this sizing calculation the conservative assumption was made that the lob-retro ΔV was equal to the impulsive boost ΔV provided by the booster ($\Delta V_{LR}=\Delta V_I$).

The sharp break-point in the curve occurs where a vehicle sized for lob-retro weighs the same as a vehicle sized to continue on to orbit. For higher booster ΔV's, the booster

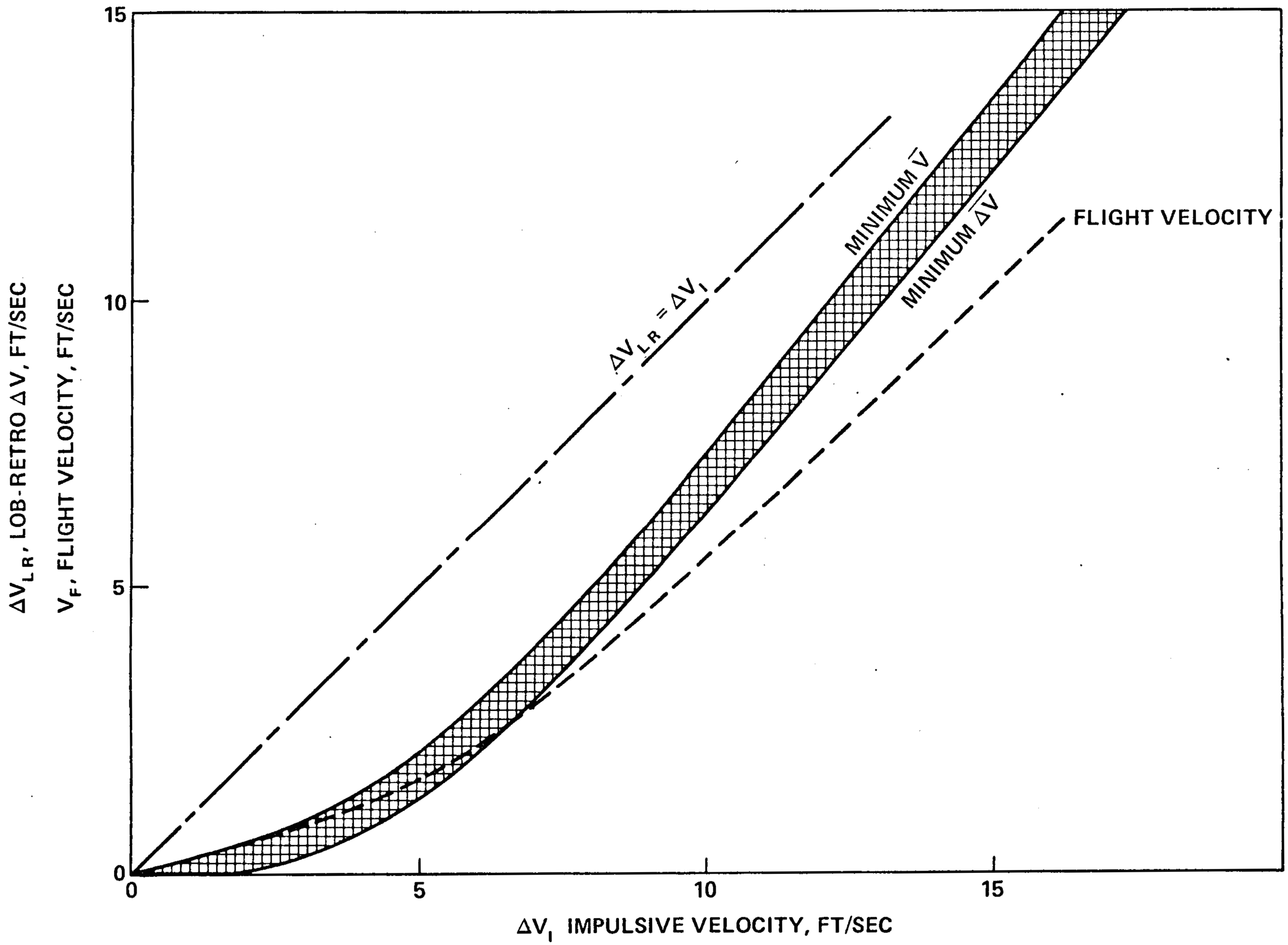

FIGURE 4. LOB-RETRO REQUIREMENTS

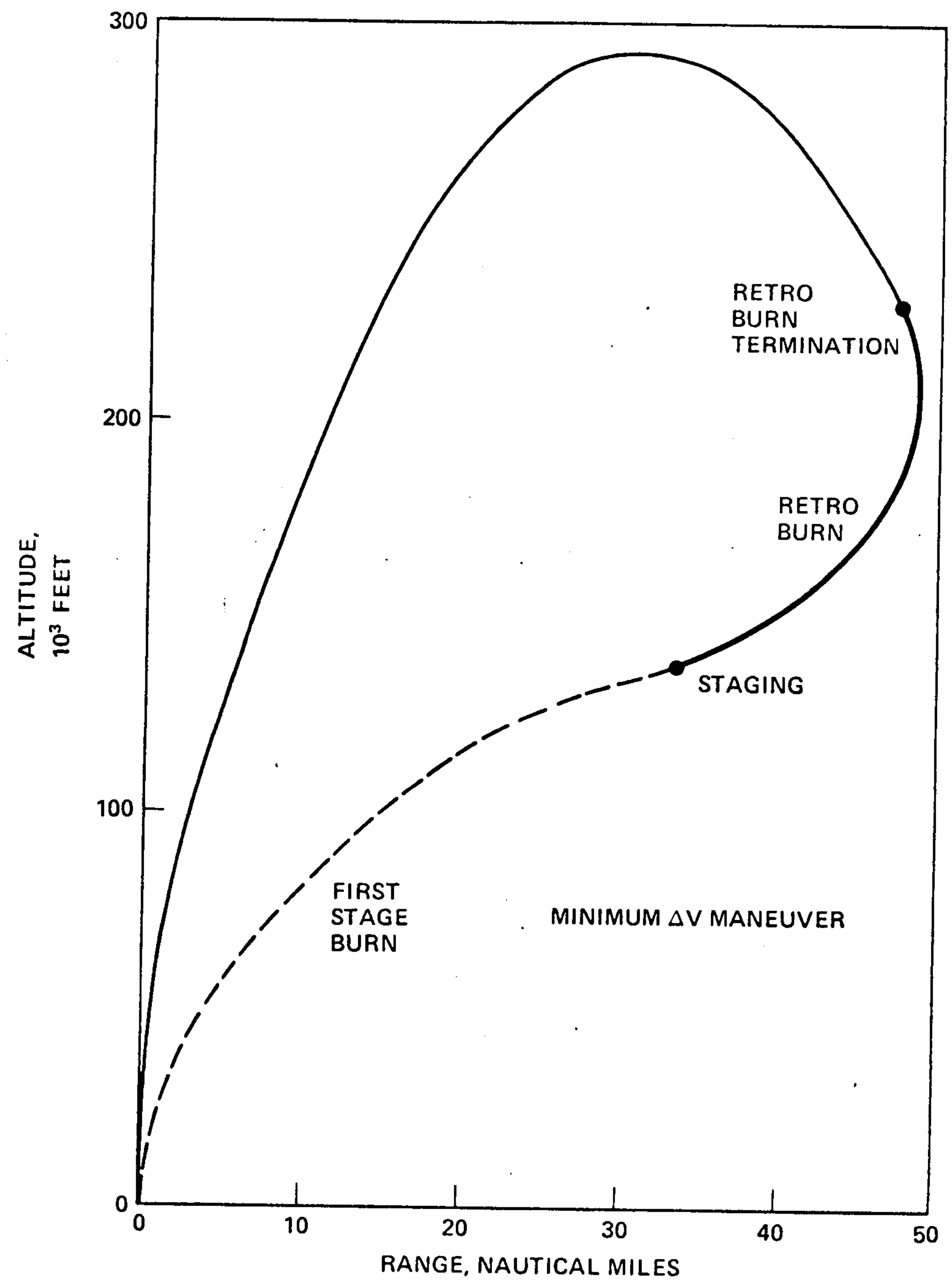

FIGURE 5. LOB-RETRO BOOSTER TRAJECTORY

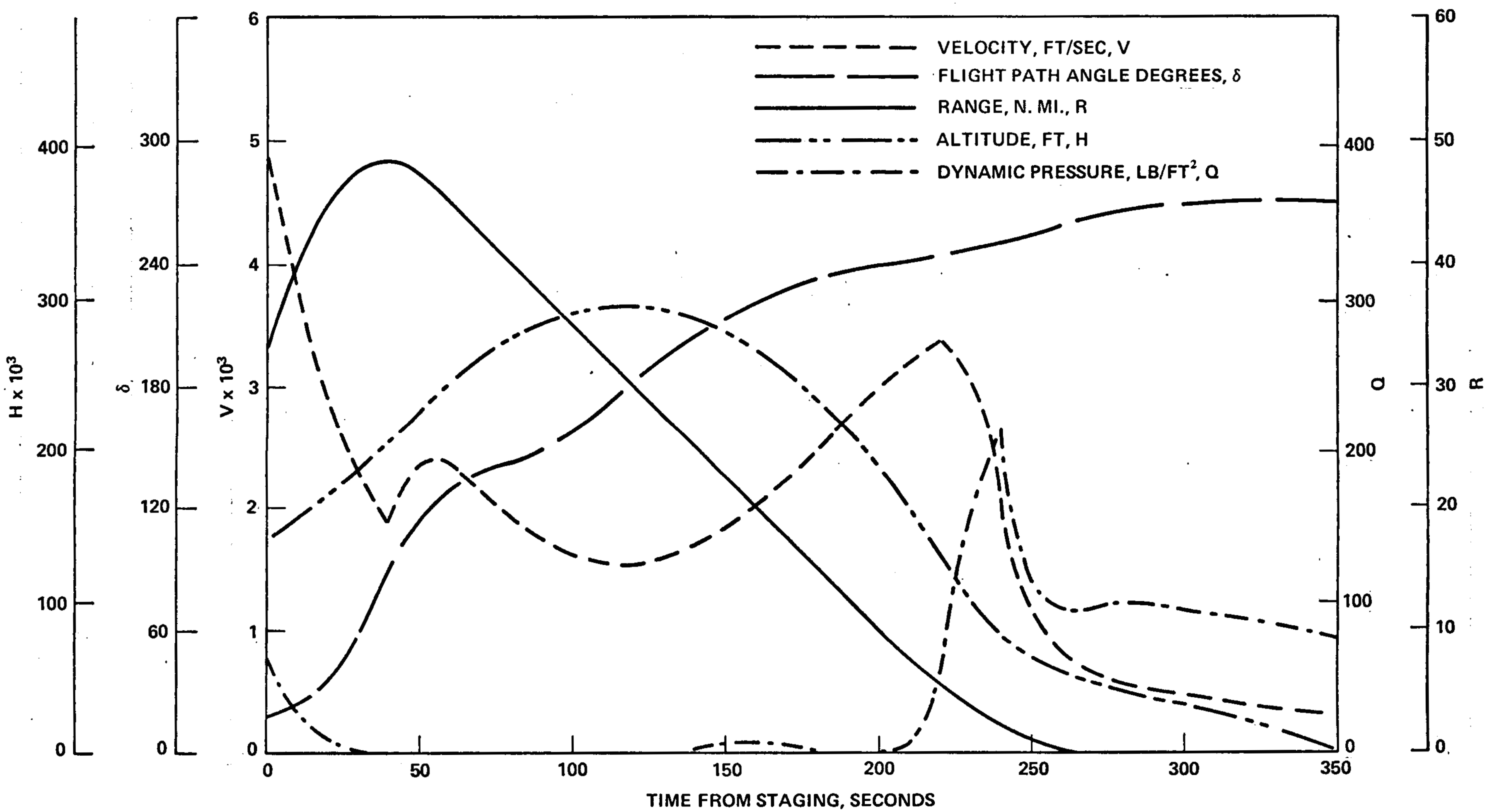

FIGURE 6. LOB-RETRO TRAJECTORY SUMMARY

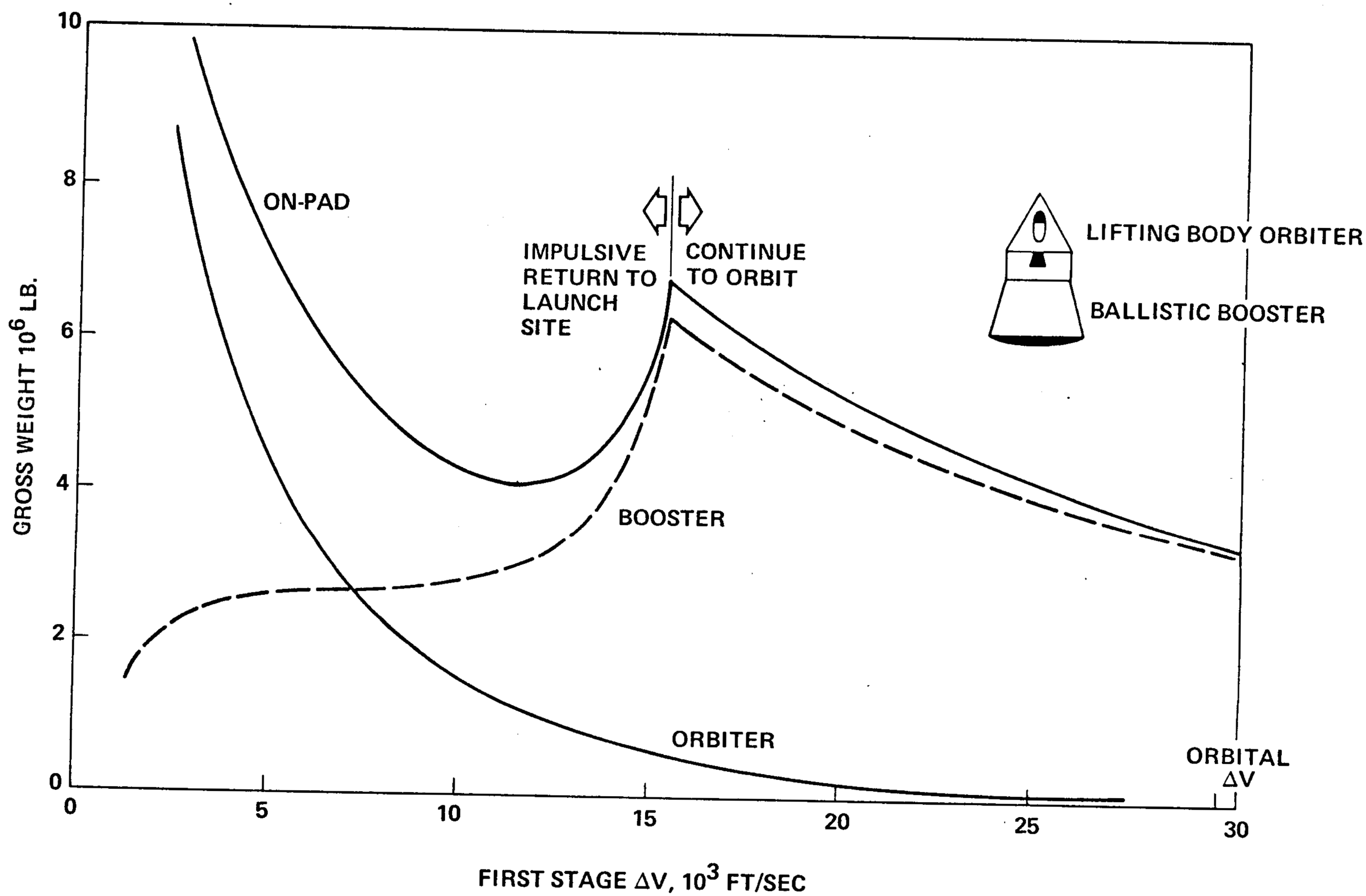

FIGURE 7. SHUTTLE SIZING
PAYLOAD 25,000 LB.

would always continue to orbit rather than lob-retro to the launch site. This scimitar shaped curve is really the superpositioning of two different curves for the different flight modes and is typical of all two-stage systems with ballistic boosters recovered at the launch site.

5.0 Conclusions

Although the lob-retro maneuver represents a startling departure from convention, preliminary investigations have not exposed any basic or fatal drawbacks. Areas that need further study are:

1. Aerodynamic effects during separation and re-orientation,

2. Dynamic effects, such as a sloshing and inertial loads that may occur because of the high pitch rates associated with re-orientation,

3. Engine restart after re-orientation.

The concept of the lob-retro maneuver is a promising way to enjoy the inherently high mass fractions of ballistic configured boosters, and still keep the low performance sensitivities of two stage systems.

EDMarion

1012-EDM-nma E. D. Marion

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